DESIGN AND CONSTRUCTION OF A MAGNETOMETER

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by

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PREFACE

An electrostatic generator, such as the 0.5 - 2.0 million electron volt (Mev) Van de Graaff machine in use at the United States Naval Postgraduate School, is, within its range the best generator for precision nuclear physics. If the otherwise excellent characteristics of the ion beam of such a generator are to be used effectively, it is essential to provide for accurate measurement of the ion particle energy. The desired accuracy should be achieved with the simplest measuring device available.

To this end a quartz fiber magnetometer was constructed for use at this institution. Since the magnetometer principle makes use of the positive ion separation magnetic field, its use is restricted to the measurement of positive ion energy.

Reproducible values of particle energy to within 0.1 per cent accuracy are obtainable.

I wish to thank Dr. E. A. Milne for suggesting this project and continuing with helpful guidance during the work.

Also, I wish to express my gratitude to Mr. M. K. Andrews and his shop personnel for their advice and assistance in the construction phases of this project.

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CHAPTER I

INTRODUCTION

1. The Need for a Magnetometer

The most general problem of nuclear physics today is to understand how nuclei are formed from the elementary particles. One of the most effective methods of research in this basic area of study involves observation of the scattering and/or transmutations which occur when a target material is bombarded with protons. In order to obtain quantitative data the proton beam must be small, well collimated, and of accurately known uniform constant energy.

The Van de Graaff electrostatic generator provides most of these beam characteristics. Its superiority over other accelerators, such as the cyclotron and linear accelerator, is due to the single DC voltage jump for the accelerated particles, thereby giving the particle energy directly to the accuracy to which the generator voltage can be stabilized. In other types of accelerators, the ion is accelerated many times by small repeated voltages and, if the particle energy is varied from the designed optimum energy, a significant loss in energy resolution results.

The Van de Graaff generator presents two difficulties to the investigator. The first is that the upper energy range is rather limited, about 12 Mev in the most advanced designs. However, many significant basic studies of nuclear bonding and particle interactions are done in this energy range. The second problem is that which is of concern in this report; the accurate measurement of particle energy. To illustrate the need for accuracy, examination of curves showing the elastic scattering of protons from carbon thirteen, obtained by Dr. E. A. Milne [3] at California

Institute of Technology, indicates that data near resonances must be taken every two to three kilo electron volts (kev) at an energy level of about 1500 kev. Energy resolution of about 0.1 per cent is clearly necessary.

2. Existing Methods of Energy Measurement

The best accuracy yet obtained for the direct measurement of electrical potentials of the order of millions of volts is in excess of ten per cent. However, there are several types of instruments which can make relative measurements at these potential levels with much better accuracy. Therefore, it is customary to calibrate a relative reading device using several secondary voltage standards, which in this case are the threshhold energies or resonance energies of certain nuclear reactions. For example, the production of neutrons when lithium is bombarded with protons occurs sharply at 1.882 $\pm$ 0.002 Mev. These calibration energy values are normally obtained by painstaking efforts with a radio frequency ion velocity gauge or a precision electro static analyzer. Relative and absolute high potential measuring techniques are described by Jennings [1] in Proceedings of the I. R. E.

The positive ion beam in Van de Graaff machines is separated selectively into mass one, two, and three hydrogen ion components[1] by being deflected about 25 degrees in a beam analyzer magnetic field. Only ions of the desired mass are directed through the exit slit. Efforts have been made to obtain fields of precisely known strength, thereby providing an absolute measure of particle energy, by way of electromagnetic force

1. mass one - hydrogen nucleus H
   mass two - singly ionized hydrogen molecule HH
   mass three - HHH

relationships. This effort has been largely unsuccessful due to difficulties in construction of large area pole faces of uniform and known field strength. The main difficulty has been the lack of precisely known corrections for the fringing field.

However, since the field strength in the beam analyzer magnet can be held constant to within 0.1 per cent, although at an unknown value, by electronic control of the magnet current, then relative measurement of the field strength becomes a practical solution to the problem of energy measurement. The magnetometer under discussion is designed to make this relative measurement.

CHAPTER II

PRINCIPLES OF MAGNETOMETER OPERATION

1. Some Design Characteristics of the Van de Graaff Generator at U. S. Naval Postgraduate School

The electrostatic generator attains a positive potential of two Mev (manually adjustable from 0.75 to 2.0 Mev). The control apparatus provides a proton beam homogeneous in energy to $\pm$0.1 per cent emerging from the slit system of the beam analyzer. This control is achieved electronically by way of a generator voltage stabilizer and a magnet current stabilizer. A functional block diagram of this control linkage is presented in figure 1.

The generating voltmeter, which is the energy measuring device provided by the manufacturer, is calibrated to indicate terminal voltage with $\pm$1.0 per cent accuracy.

2. Principles of Magnetometer Operation

Given the stabilized magnet current described above, with the consequent stable magnetic field, a magnetometer can be designed to measure the relative field to the accuracy of the field stability. In the unsaturated region of magnet operation it is sufficient to measure the values of the fringing field, since it remains proportional to the central field. In the saturated region calibration corrections must be introduced. In the energy range of the Van de Graaff accelerator described above, the necessary magnet current is below saturation level.

If a coil of area, A, carrying current, I, is placed with the coil plane parallel to a uniform magnetic field, B, the resulting torque, T,

will amount to:

$$T = NIBA$$

If a mechanical torque is applied to the coil such as to maintain the coil plane parallel to the field, then:

(1) $T = NIBA = \text{a constant, say } k_1$

The preceeding equation defines the force relationship in a magnetic null-reading device.

If protons of energy, E, pass through the field, B, they are deflected in a circle of radius, r; the force relationship is:

$$Bev = \frac{mv^2}{r}$$

It is noted that the relativistic corrections for proton mass in the 0-2 Mev energy range is much less than 0.1 per cent. The equation above is valid here. Also, the radius, r, is fixed by the geometry of the beam analyzer and exit slit system.

After squaring both sides of the above equation and substituting $\frac{mv^2}{2} = E$, the strength of the field is:

(2) $B = \frac{(2m)^{\frac{1}{2}}}{er} E^{\frac{1}{2}} = k_2 E^{\frac{1}{2}}$

Substituting the value of B from equation (2) into equation (1):

$$k_1 = NIA\, k_2\, E$$

or: (3) $I = \frac{k_1}{k_2\, NA} \frac{1}{E^{\frac{1}{2}}} = \frac{k_3}{E^{\frac{1}{2}}}$

If the energy of the particles is steady within 0.1 per cent, then the relative energy may be read to this accuracy by measuring coil current reproducibly to 0.1 per cent.

If the coil current is measured by potentiometer, V, across a precision resistor, equation (3) becomes:

(4) $\frac{V}{R} = \frac{k_3}{E}$ or; $E = \frac{k}{V^2}$

Therefore, if the conditions described above are the basis for a magnetometer design, the quantity $\frac{1}{V^2}$ is a linear function of proton energy.

CHAPTER III

CONSTRUCTION OF THE MAGNETOMETER AND ASSOCIATED INDICATOR AND CONTROL CIRCUITS

1. Construction of the Magnetometer

Sketches of the completed magnetometer are shown in figures 2 and 3. All materials used in construction are non-magnetic.

The magnetometer coil consists of 20 turns of enameled magnet wire on a lucite bobbin, which is lined with an aluminum ring for magnetic damping of the coil motion. A mirror, an element of the indicating system to be described, is mounted on the side of the coil. The coil is supported with its axis in a horizontal position by the tension in a brass spring.

The spring is constructed from four turns of No. 32 brass spring wire flattened in cross section to a five to one rectangle. The spring serves a second purpose as the positive current lead to the coil winding. The negative coil lead is grounded to the frame through a piece of very fine copper wire.

Mechanical stops, holding coil rotation to ± 2.5 degrees are provided by tungsten wire fingers extending from a coil diameter. These fingers are restricted to one half centimeter motion at the ends.

Mechanical torque is placed on the coil by a quartz fiber 150 microns in diameter and about six centimeters long. Torque elements of materials other than quartz, such as the phosphor bronze springs found in conventional jeweled meter movements and as used by Lauritzen and Lauritzen [2] in construction of a spectrograph "fluxometer" are not satisfactory for use with the Van de Graaff machine. Hysteresis in steel pivots and creep plus hysteresis in metallic springs prevent achievement of 0.1 per cent reproduc-

ibility. Desirable characteristics of quartz include:

a. Low viscosity - 1/1000th that of metals

b. Low temperature coefficient of rigidity modulus - measured by Milne [4] as about 1/5th that of phosphor bronze

c. Low temperature coefficient of expansion

d. Negligible hysteresis - Measured by Milne as less than 0.05 per cent as compared to 0.4 per cent for phosphor bronze.

It is noted that hysteresis and creep in the brass tension spring, described above, do not enter as a problem, since the coil stops prevent significant spring movement.

The quartz fiber was made using the techniques described by Professor H. V. Neher [5]. The fiber was fused to cross pieces of 500 micron quartz at the ends. The two cross pieces were waxed to the torque shaft and a lucite bobbin tab respectively.

A zero set plate was provided in conjunction with the torque lever to permit periodic checking of the original calibration null and adjustment if necessary. "On" and "Off" stops are fixed on the plate, which is adjustable in position about the torque shaft axis. With the torque lever in the "Off" position, and with zero coil current, the plate is adjusted with a set screw to the desired null. Shifting the lever to the "On" position twists the quartz fiber about 140 degrees, rotating the coil until it comes to rest against the mechanical stops in readiness for metering.

The coil current is then increased until null position is again reached and the current measured.

The magnetometer was bench tested using a 2000 gauss permanent magnet

to provide the magnetic field and the motion of a lamp filament image on a ruled scale 24 inches from the coil mirror as an indicating system. The coil current was controlled with two variable resistors of 500 ohms and five ohms in series with dry cell batteries, totaling nine volts potential. The current at null position was measured with a precision potentiometer, calibrated against a standard cell, across a 10 ohm resistor. With this relatively crude indicating system, readings of precision resistor voltage at magnetometer null were reproduced within 0.2 per cent. The variation between any two readings never exceeded 0.2 per cent. The average reproducibility was 0.08 per cent.

2. Construction of the Indicator Circuit

The indicating system used must be accurate to within 0.1 per cent to maintain the overall magnetometer accuracy.

The system selected is shown in figure 4 and described below.

The beam from a point light source is reflected from the coil mirror to a triply reflecting mirror arrangement and finally to a double phototube and galvanometer circuit which indicates the coil position relative to null position. The triple mirror arrangement is used to permit a compact installation. The third mirror of the system is spherically concave to provide focussing of the light image on the phototubes. Reference to figure 3 is suggested as the best description of the mirror system.

The light beam strikes the aluminized surfaces (bounding the right angle on an isosceles prism) and is reflected to either one or both of two phototubes which are connected to a simple balancing circuit. Null position is indicated by zero deflection on a galvanometer and occurs when the light beam is splitting across the right angle of the prism.

3. Calibration of the Magnetometer

Nuclear reactions which are suitable for calibration purposes include:

a. Li(p,n) E =1.882 $\pm$(0.002) Mev

b. Al(p,gamma) E =0.9933 Mev
(Resonance type calibration point)

c. F(p,gamma) E =0.8735 Mev
(Resonance type)

Of these, the Li(p,n) is the most widely used in physics laboratories today. The calibration procedure includes the following steps: (For example purposes, the Li(p,n) reaction is considered)

a. Set the Van de Graaff energy at a nominal value using the equipment generator voltmeter, for example, 1.85 Mev.

b. Place a scintillation counter and associated equipment so as to detect any neutrons generated in the lithium target.

c. Increase the accelerator energy in small increments recording magnetometer voltage, V, at null magnetometer position and scintillator neutron counts (initially zero).

d. At the reaction threshold a sharp appearance of neutron counts is noted. The magnetometer reading at the threshold energy (1.882 $\pm$0.002 Mev) is then known precisely.

Since a calibration curve of Energy versus $1/V^2$ is linear, calibration at two points suffices to determine the entire calibration. Below analyzer magnet saturation there is no reason to expect deviations from a straight line between calibration points.

The work described under "3. Calibration of the Magnetometer" was not completed at the time of this writing.

BIBLIOGRAPHY

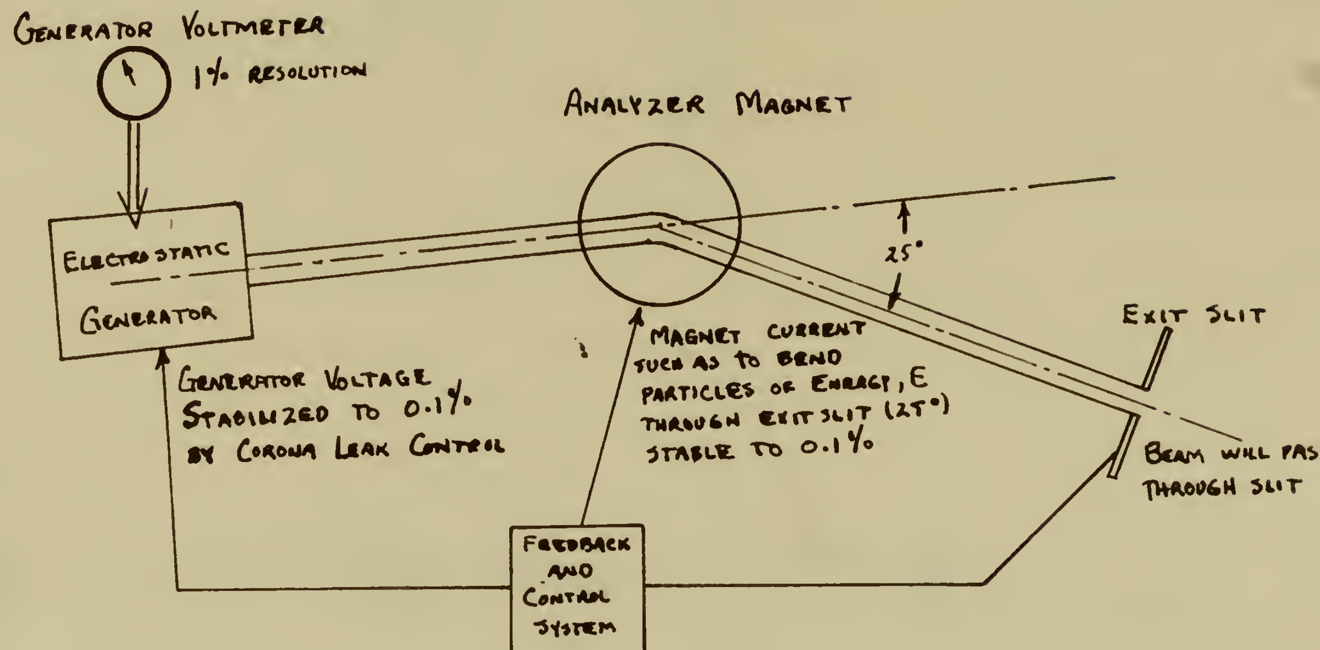
1. Jennings, Burridge — ELECTRONICS AND THE ELECTROSTATIC GENERATOR
Proc. I.R.E., Vol. 38, No. 10, October 1950

2. Lauritzen, C. C. and Lauritzen, T. — A NULL READING FLUXOMETER
Rev. Sc. Instr., Vol. 19, No. 12, p 916, December 1948

3. Milne, E. A. — ENERGY LEVELS IN N^{14} FROM THE SCATTERING OF PROTONS BY C^{13}
Phys. Rev., Vol. 93, No. 4, pp 762-767, February 1954

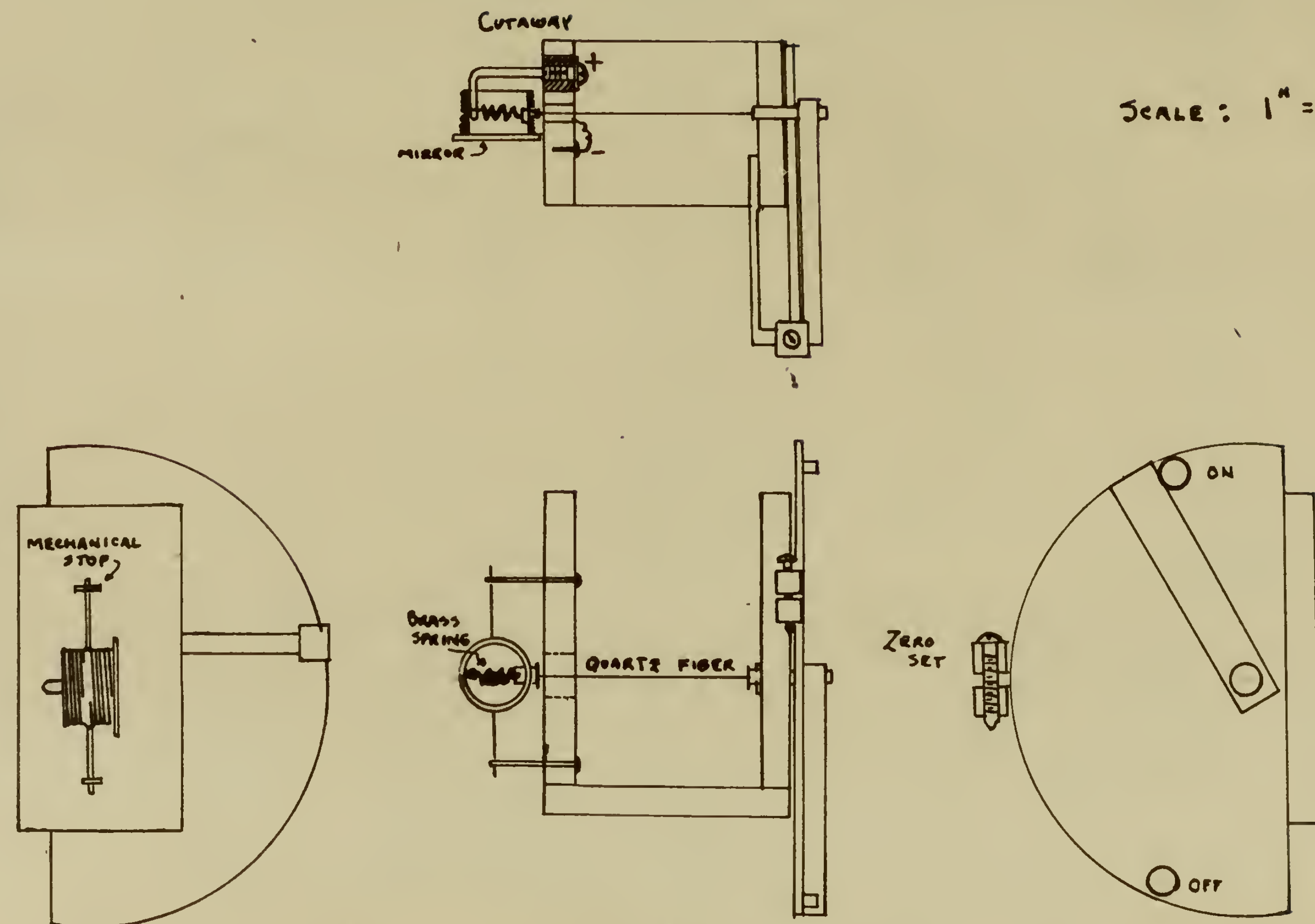
4. Milne, E. A. — ELASTIC SCATTERING OF PROTONS BY CARBON 12 AND CARBON 13
Ph.D. Thesis, California Institute of Technology, 1953 (Unpublished)

5. Strong, J — PROCEDURES IN EXPERIMENTAL PHYSICS
Prentice Hall, pp 188-216 (1938)



VAN DE GRAAFF ENERGY STABILIZING SYSTEM

FIGURE 1



SCALE : 1" = 2"

SKETCH OF THE MAGNETOMETER SHOWING FOUR VIEWS

FIGURE 2

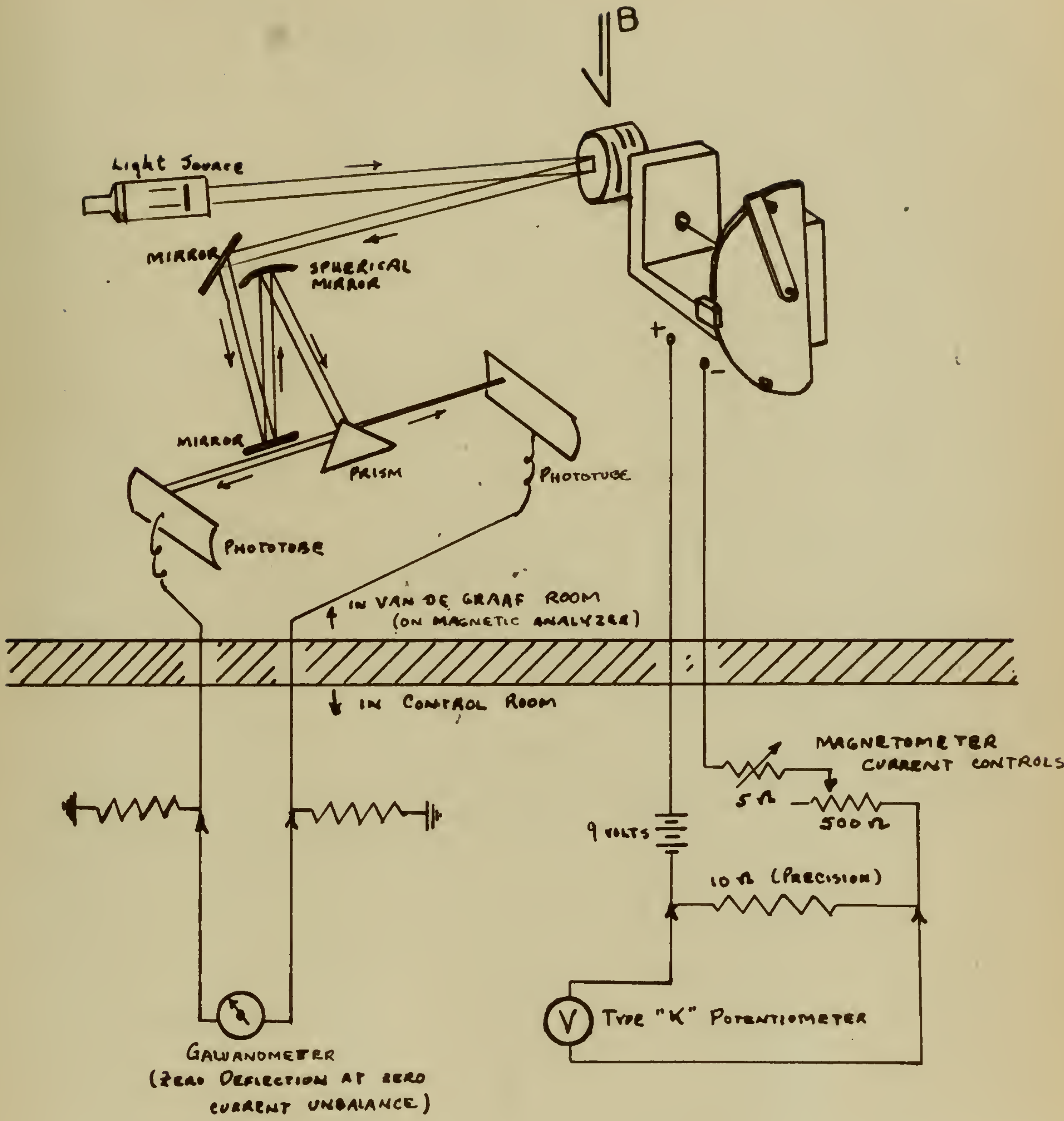


DIAGRAM OF THE MAGNETOMETER SYSTEM

FIGURE 3

Sketch of Magnetometer in operating position

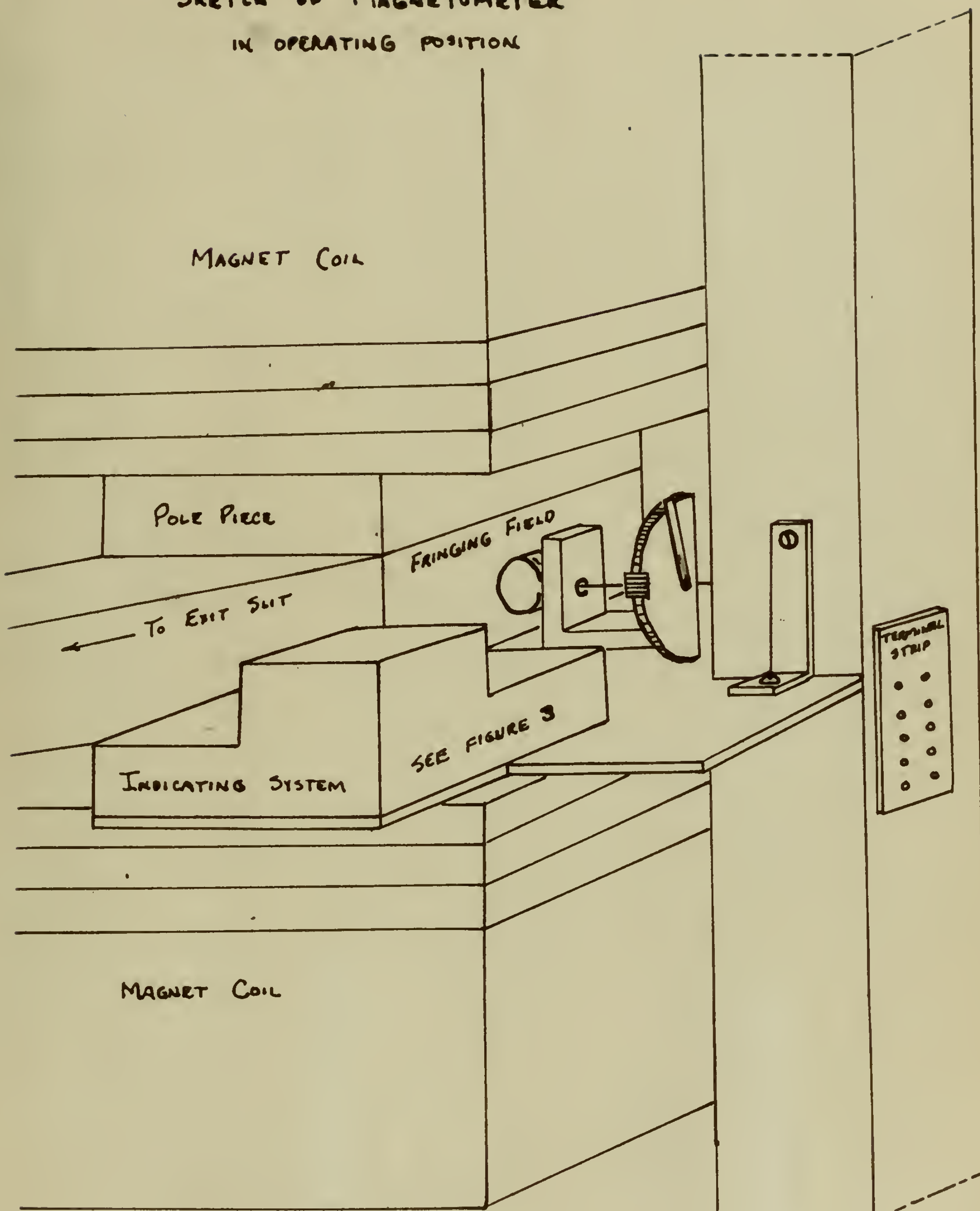


Figure 4

Wells
Design and construction of a magnetometer.

Thesis
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Besign and construction of a magnetometer.